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CHARM SPECTROSCOPY IN DELPHI

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Invited talk given at
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Frascati (Rome) - Italy

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on behalf of the DELPHI collaboration

ABSTRACT

The production of charmed particles has been studied using 3.5 milllion hadronic Z decays collected by the DELPHI collaboration at LEP between 1992 and 1995. Large samples of D meson decays have been exclusively reconstructed, allowing to look for $D^*\pi$ and $D^*\pi\pi$ final states. The production fractions of the narrow $D_1^0(2420)$ and $D_2^{*0}(2460)$ orbital states are measured in c and b quark jets separately. Evidence for a radial state $D^{*\prime}(2637)$ is presented in the $D^{*+}\pi^+\pi^-$ decay mode.

1 Introduction

In the spectroscopy of charm mesons, the D and D^* ground states are well established while only the narrow orbital excitations D_1 and D_2^* have been clearly observed so far [1]. For mesons containing heavy and light quarks $(Q\overline{q})$ and in the limit where the heavy quark mass is much larger than the typical QCD scale ($m_Q \gg \Lambda_{QCD}$), the spin $\vec{s}_Q$ of the heavy quark and the total (spin+orbital) angular momentum $\vec{j}_q = \vec{s}_q + \vec{L}$ of the light component are separately conserved by the strong interaction [2]. This heavy quark symmetry, together with quark potential models used for lower mass mesons, allows the masses and decay widths of heavy mesons of total spin $\vec{J} = \vec{s}_Q + \vec{j}_q$ to be predicted [3]. The D and D^* correspond to the two degenerate levels of the

Table 1: *Expected and observed orbital excitations of D^0 and D^+ mesons. The broad ($L = 1$, $j_q = 1/2$) states are estimated. The narrow $j_q = 3/2$ states are measured. Predicted decay modes not yet observed are indicated within parentheses.*

	J^P j_q		Mass (MeV/c^2)	Γ Width (MeV/c^2)	Decay modes
D_0^*	0^+ 1/2		~ 2360	≥ 170	$(D\pi)$
D_1'	1^+ 1/2		~ 2430	≥ 250	$(D^*\pi)$
D_1	1^+ 3/2	D_1^+	2427 ± 5	28 ± 8	$D^{*0}\pi^+$ $(D^{*+}\pi^0$, $D\rho$, $D\pi\pi)$
		D_1^0	2422.2 ± 1.8	$18.9^{+4.6}_{-3.5}$	$D^{*+}\pi^-$ $(D^{*0}\pi^0$, $D\rho$, $D\pi\pi)$
D_2^*	2^+ 3/2	D_2^{*+}	2459 ± 4	25^{+8}_{-7}	$D^0\pi^+$, $D^{*0}\pi^+$ $(D^{(*)+}\pi^0$, $D^*\rho$, $D^*\pi\pi)$
		D_2^{*0}	2458.9 ± 2.0	23 ± 5	$D^+\pi^-$, $D^{*+}\pi^-$ $(D^{(*)0}\pi^0$, $D^*\rho$, $D^*\pi\pi)$

($L = 0$, $j_q = 1/2$) state. The $L = 1$ orbital excitations are grouped into two degenerate levels with $j_q = 1/2$ and $j_q = 3/2$. The $j_q = 1/2$ states decay through an S-wave and are expected to have a large decay width, whereas the $j_q = 3/2$ states decay through a D-wave and are narrow. This scheme is summarized in Table 1 for non-strange charmed mesons. The $D_1(2420)$ and $D_2^*(2460)$ have been observed with decay widths of about 20 MeV/c^2 and are identified as the states with $j_q = 3/2$ and $J^P = 1^+$ and 2^+, respectively [1]. Orbitally excited beauty mesons are expected to present a similar scheme.

In addition to these orbital excitations, radial excitations of heavy mesons are also foreseen. Based on a QCD inspired relativistic quark model, the D' ($J^P = 0^-$) and $D^{*'}$ ($J^P = 1^-$) are expected with masses of 2.58 GeV/c^2 and 2.64 GeV/c^2, respectively, with a 10-25 MeV/c^2 uncertainty on the mass predictions [4]. A more recent relativistic quark model, which requires no expansion in function of the lightest quark mass, predicts masses of 2.58 GeV/c^2 and 2.63 GeV/c^2, respectively, with an agreement of better than 20 MeV/c^2 for the observed charm orbital states [5]. The dominant decay modes of the D' and $D^{*'}$ are expected to be into $D\pi\pi$ and $D^*\pi\pi$, respectively, but decays into $D^{(*)}\rho$ or through an intermediate orbital excitation are not excluded. Decays with a single pion in the final state would require a P-wave transition and should be suppressed. Figure 1 shows the expected spectrum of the various D mesons with their decay modes involving S-, P- or D-wave transitions.

The production of orbitally and radially excited charmed states are discussed in the following. First, simple counting arguments, although model dependent [6], of D^0, D^+ and D^{*+} in $c\bar{c}$ and $b\bar{b}$ events show that charm states of heavier

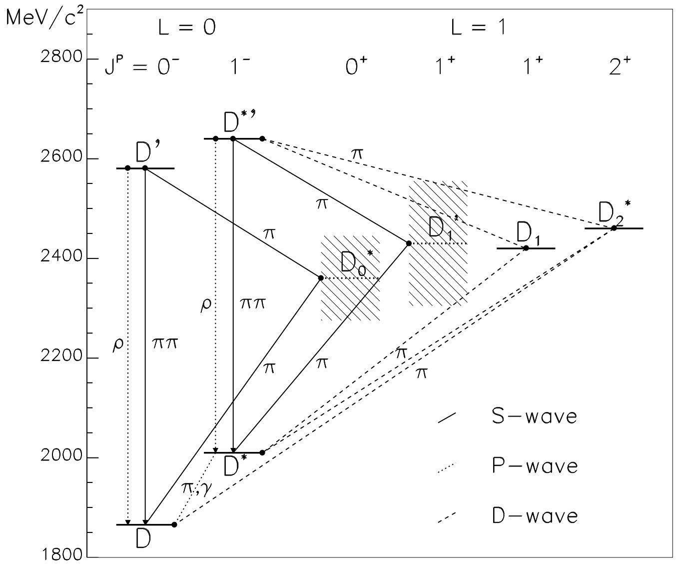

Figure 1: *Spectroscopy of non-strange D mesons. The shaded areas show predicted widths for these states. For clarity the expected D_1 and D_2^* decays involving a ρ meson or $\pi\pi$ pair are not shown.*

masses should contribute to the observed rates of ground states D mesons [1]. Then the narrow orbital $D_1(2420)$ and $D_2^*(2460)$ states, decaying into $D^{*+}\pi^-$ are observed in c and b quark jets, separately. Looking for the $D^{*+}\pi^+\pi^-$ final state a narrow signal is observed, which is interpreted as a $D^{*'}(2637)$ radial state.

2 Tagging of c and b quark jets

The DELPHI detector consists of several independent devices for tracking, calorimetry and particle identification [7)]. A total of 3.5 million hadronic Z decays events was obtained from the 1992-1995 data at centre-of-mass energies close to the Z mass. This corresponds to 1.2 (1.5) million c (b) quark jets produced. Charmed mesons from Z→ $b\bar{b}$ events were distinguished from those in $c\bar{c}$ events by considering both their energy and lifetime informations.

In $b\bar{b}$ events each bottom quark fragments into a B hadron which subsequently decays to a D meson, whereas in $c\bar{c}$ events charmed mesons are directly produced in the fragmentation process. This difference in the hadronisation leads to a larger energy of D from primary charm quark (22 GeV in average) and a softer spectrum from bottom quark events (14 GeV in average).

[1]Throughout the paper charge-conjugate states are implicitly included and the pion from the D^{*+} decay is denoted π_*^+.

The apparent decay length ΔL, or proper time $\Delta t = \Delta L \cdot M(\mathrm{D})/p_t(\mathrm{D})$, of the reconstructed D mesons are also efficient variables to select $\mathrm{b\overline{b}}$ enriched samples. For a $\mathrm{D^0}$ meson from charm quark fragmentation, Δt is the $\mathrm{D^0}$ proper decay time and is on average 0.4 ps [1]. For a $\mathrm{D^0}$ from B decay, Δt is usually larger than the mean B lifetime of 1.6 ps [1]. From the simulation, selecting $\mathrm{D^0}$ decays with $\Delta t > 1$ ps would retain about 10% from $\mathrm{c\overline{c}}$ events and 60% from $\mathrm{b\overline{b}}$ events.

Due to the relatively long lifetimes of charmed and bottom particles, the heavy flavour events are characterised by the presence of secondary vertices. A variable P_E was defined as the probability that all charged particle tracks detected in the event came from the primary vertex [7]. This variable was much smaller in $\mathrm{b\overline{b}}$ events than in $\mathrm{c\overline{c}}$ or light quark events. Typically a 90% purity was achieved for 60% of $\mathrm{b\overline{b}}$ events by selecting P_E values less than 10^{-2}.

3 Charm counting in $\mathrm{c\overline{c}}$ and $\mathrm{b\overline{b}}$ events

A combined fit to the D meson energy and P_E information [8], lead to the production rates quoted in Table 2. Isospin conservation suggests equal production rates of charged ($\mathrm{c\overline{d}}$) and neutral ($\mathrm{c\overline{u}}$) D mesons in the fragmentation of charm quarks in $\mathrm{c\overline{c}}$ events. A difference in the observed $\mathrm{D^0}$ and $\mathrm{D^+}$ rates could arise from the difference between the $\mathrm{D^{*0}}$ and the $\mathrm{D^{*+}}$ decay rates. The $\mathrm{D^{*+}}$ can decay into $\mathrm{D^0}\pi^+$, $\mathrm{D^+}\pi^0$ or $\mathrm{D^+}\gamma$ while, due to their masses, the $\mathrm{D^{*0}}$ can only decay into $\mathrm{D^0}\pi^0$ or $\mathrm{D^0}\gamma$ [1]. Therefore the observed rate of $\mathrm{D^{*+}} \to \mathrm{D^0}\pi^+$ could be responsible for the difference between the $\mathrm{D^0}$ and $\mathrm{D^+}$ production rates.

If $f_d(c)$ is defined as the probability for a charm quark to fragment into a primary charged D or $\mathrm{D^*}$ meson (assumed equal to $f_u(c)$), then the probabilities for a charm quark to fragment into the observed $\mathrm{D^{*+}}$, $\mathrm{D^0}$ and $\mathrm{D^+}$ are expressed as:

$$\begin{aligned} P_{c\to D^{*+}} B_* &= Y\, f_d(c) \\ P_{c\to D^0} &= (1+Y)\, f_d(c) \\ P_{c\to D^+} &= (1-Y)\, f_d(c) \end{aligned} \tag{1}$$

where $B_* = BR(\mathrm{D^{*+}} \to \mathrm{D^0}\pi^+)$ and $Y = B_* \cdot \frac{V}{V+P}$ where $\frac{V}{V+P}$ is defined as the ratio of the vector meson rate to the total vector+pseudoscalar meson rate. The Y value can be obtained for $\mathrm{c\overline{c}}$ events from a fit to equation 1 using the result from Table 2:

$$\frac{V}{V+P} = 0.620 \pm 0.014(stat) \pm 0.014(syst) \pm 0.025(BR)\,, \tag{2}$$

at four sigma below the naive spin counting expectation of 0.75, suggesting an eventual production of $\mathrm{D^*}$ and D mesons from decays of higher D mass states.

Table 2: *Measured $R_{c(b)}P_{c(b)\to D}BR(D\to X)$ with stat. and syst. errors.*

Mode	$R_cP_{c\to D}\ BR\times 10^3$	$R_bP_{b\to D}\ BR\times 10^3$	correlation
$D^0\to K^-\pi^+$	$3.570\pm 0.100\pm 0.146$	$4.992\pm 0.162\pm 0.304$	-0.46
$D^+\to K^-\pi^+\pi^+$	$3.494\pm 0.116\pm 0.140$	$4.525\pm 0.204\pm 0.226$	-0.38
$D^{*+}\to (K^-\pi^+)\pi^+$	$1.089\pm 0.027\pm 0.039$	$1.315\pm 0.035\pm 0.053$	-0.34

Table 3: *Measured D_J multiplicities in b and c quark jets.*

(%)		$\mathrm{D}_1^0(2420)$		$\mathrm{D}_2^{*0}(2460)$	
$f(\mathrm{b}\to\mathrm{D}_J)$	DELPHI	2.0 ± 0.6	$(stat)$	4.8 ± 2.0	$(stat)$
	OPAL	5.0 ± 1.5	$(stat+syst)$	4.7 ± 2.7	$(stat+syst)$
	ALEPH	2.3 ± 0.7	$(stat+syst)$	<2.0	$(95\%\ C.L.)$
$f(\mathrm{c}\to\mathrm{D}_J)$	DELPHI	1.9 ± 0.4	$(stat)$	4.7 ± 1.3	$(stat)$
	OPAL	2.1 ± 0.8	$(stat+syst)$	5.2 ± 2.6	$(stat+syst)$
	ALEPH	1.6 ± 0.4	$(stat+syst)$	4.7 ± 1.0	$(stat+syst)$
	CLEO	1.8 ± 0.3	$(stat+syst)$	1.9 ± 0.3	$(stat+syst)$
	theory	1.7		2.4	

4 Study of $\mathbf{D}_1$ and $\mathbf{D}_2^*$ production in c and b quark jets

A direct search of the $\mathrm{D}_1^0(2420)$ and $\mathrm{D}_2^{*0}(2460)$ orbital states decaying into $\mathrm{D}^{*+}\pi^-$ was thus performed [9]. The D^{*+} were exclusively reconstructed in the $\mathrm{D}^{*+}\to\mathrm{D}^0\pi^+_*$ decay mode followed by $\mathrm{D}^0\to\mathrm{K}^-\pi^+$ or $\mathrm{D}^0\to\mathrm{K}^-\pi^+\pi^+\pi^-$: a total of 7400 D^{*+} was obtained. High purity ($\simeq 90\%$) $\mathrm{b\bar{b}}$ and $\mathrm{c\bar{c}}$ samples were selected separately using both the energy and lifetime informations. Any additional pion of momentum larger than $1-1.5$ GeV/c and charge opposite to that of the D^{*+} was used to fit a $\mathrm{D}^0\pi^+_*\pi^-$ vertex. The pion selection efficiency was estimated to be about 60%.

To evaluate the $M(\mathrm{D}^{*+}\pi^-)$ invariant mass, the following mass difference was computed: $M(\mathrm{D}^{*+}\pi^-) = M(\mathrm{D}^0\pi^+_*\pi^-) - M(\mathrm{D}^0\pi^+_*) + m_{\mathrm{D}^*}$ where m_{D^*} is the nominal D^{*+} mass [1]. This gives a resolution σ of about 6 MeV/c^2 on $M(\mathrm{D}^{*+}\pi^-)$, according to the simulation. The $M(\mathrm{D}^{*+}\pi^-)$ invariant mass distribution is presented in Figure 2 for the selected $\mathrm{b\bar{b}}$ and $\mathrm{c\bar{c}}$ enriched samples (data points). An excess of $(\mathrm{D}^{*+}\pi^-)$ pairs is observed between 2.4 and 2.5 GeV/c^2 , but not in the $M(\mathrm{D}^{*+}\pi^+)$ distribution (hatched histogram). The $(\mathrm{D}^{*+}\pi^-)$ mass spectrum was fitted as the sum of three contributions: a background function of the form $\alpha(M(\mathrm{D}^*\pi)-m_{\mathrm{D}^*}-m_\pi)^\beta\cdot\exp(-\gamma(M(\mathrm{D}^*\pi)-m_{\mathrm{D}^*}-m_\pi))$ where m_π is the pion mass and α, β and γ are free parameters; for each D_1^0 and D_2^{*0} resonance, the convolution of a Breit-Wigner

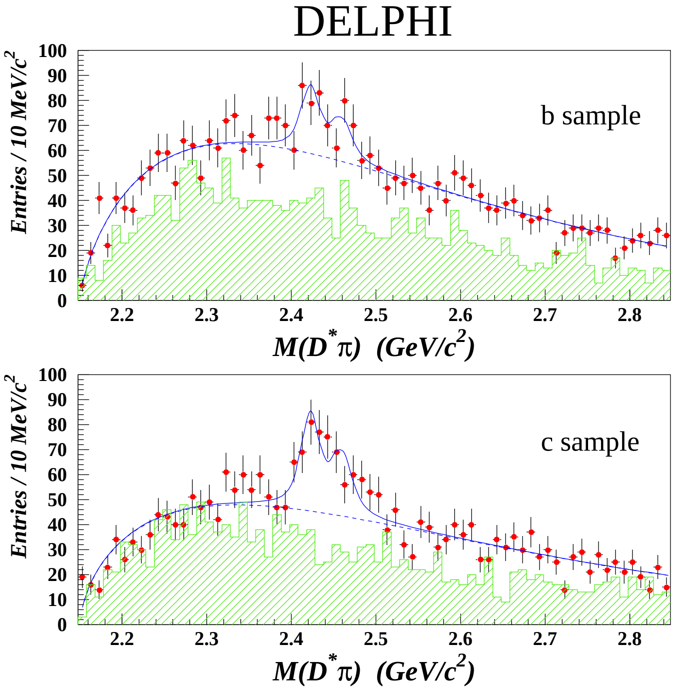

Figure 2: *Invariant mass ($D^{*+}\pi^-$) (dots) and ($D^{*+}\pi^+$) (hatched histogram).*

function and a Gaussian describing the experimental mass resolution. Fixing the mass and width of both resonances to their world average value [1], the number of fitted D_1^0 and D_2^{*0} was 166 ± 37 (245 ± 37) in the $\mathrm{b\bar{b}}$ $(\mathrm{c\bar{c}})$ enriched sample.

Knowing from the simulation the efficiencies and purities in both $\mathrm{b\bar{b}}$ and $\mathrm{c\bar{c}}$ samples, the production fractions of both D_J states are reported in Table 3. They are found in agreement with other CLEO and LEP measurements [10], as well as a theoretical estimate of direct D_J production in charm quark fragmentation [11].

5 Search for a radially excited D meson

Repeating a similar procedure as above, all remaining opposite charge $\pi^+\pi^-$ pairs produced in the same direction as the D^{*+} candidates were used to fit a $\mathrm{D}^0\pi^+\pi^-$ vertex [12]. The additional pions were required to have a momentum larger than $0.6 - 1.0$ GeV/c and not to be identified as kaons. As previously, $\mathrm{D}^{*+}\pi^+\pi^-$ combinations belonging in $\mathrm{b\bar{b}}$ or $\mathrm{c\bar{c}}$ enriched samples were selected. The reconstructed invariant mass was computed as $M(\mathrm{D}^{*+}\pi^+\pi^-) = M(\mathrm{D}^0\pi_*^+\pi^+\pi^-) - M(\mathrm{D}^0\pi_*^+) + m_{\mathrm{D}^*}$. This gave a resolution of about 6 MeV/c^2 and no bias, according to the simulation. The invariant mass distribution of all $\mathrm{D}^{*+}\pi^+\pi^-$ candidates is presented in Figure 3. A narrow peak is observed whereas the wrong charge combinations $\mathrm{D}^{*+}\pi^-\pi^-$ do

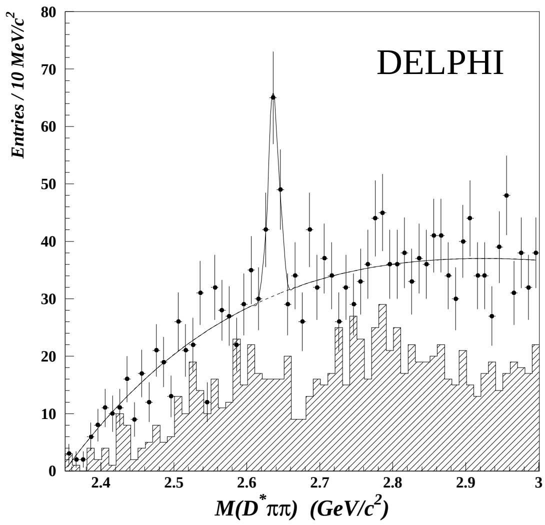

Figure 3: *Invariant mass ($D^{*+}\pi^+\pi^-$) (dots) and ($D^{*+}\pi^-\pi^-$) (hatched histogram).*

not show any excess. A binned maximum likelihood fit to the mass distribution was performed by taking into account two contributions: a function of the form $\alpha(M(\mathrm{D}^*\pi\pi) - m_{\mathrm{D}^*} - \mu)^\beta \cdot \exp(-\gamma(M(\mathrm{D}^*\pi\pi) - m_{\mathrm{D}^*} - \mu))$ for the background, with μ set to 340 MeV/c^2, and a Gaussian function with free parameters to describe the narrow peak. The fitted number of events was $66 \pm 14(stat)$. The fitted width was $7 \pm 2(stat)$ MeV/c^2, in agreement with the expected resolution, and the average mass was found to be $2637 \pm 2(stat) \pm 6(syst)$ MeV/c^2, where the systematic error was evaluated from a fit to the narrow D_J resonances of the previous section. About $(57 \pm 10)\%$ of these events were selected in the $c\bar{c}$ enriched sample. A Breit-Wigner form was also used to fit the signal shape, giving a 95% C.L. upper limit of 15 MeV/c^2 for the full decay width of the resonance.

The observed signal is interpreted to come from a $\mathrm{D}^{*'}$ radial excitation ($2^3\mathrm{S}_1$) with an expected mass of about $2630 - 2640$ MeV/c^2 [4, 5]. It is however important to stress that recent theoretical computations of the expected width would predict a much larger value for such a radial excitation [13].

The production rate of $\mathrm{D}^{*'}$ relative to that of D_1^0 and D_2^{*0} was evaluated:

$$\frac{< N_{\mathrm{D}^{*\prime +}} > Br(\mathrm{D}^{*\prime +} \to \mathrm{D}^{*+}\pi^+\pi^-)}{\sum_{J=1,2} < N_{\mathrm{D}_J^{(*)0}} > Br(\mathrm{D}_J^{(*)0} \to \mathrm{D}^{*+}\pi^-)} = 0.49 \pm 0.18(stat) \pm 0.10(syst). \qquad (3)$$

This can be compared with models of primary hadron production which predict 0.16 ± 0.01 [11] or 0.25 ± 0.02 [14] for $c\bar{c}$ events. The measured value in Z decays, where both $c\bar{c}$ and $b\bar{b}$ events contribute, is larger than these expectations but has a large uncertainty.

6 Conclusion

The study of charm meson excited states can still be improved at LEP. Other decay channels (into $D\pi$ or DK) can also be used in DELPHI. The study of the production rate of both narrow and broad D_J states can be achieved in B semileptonic decays, maybe providing a nice way to evaluate the mass and width of the broad states.

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References

1. Review of Particle Physics, Eur. Phys. J. **C3** (1998) 1.
2. N. Isgur and M.B. Wise, Phys. Rev. Lett. **66** (1991) 1130 and ref. therein.
3. J. Rosner, Comments on Nucl. and. Part. Phys. **16** (1986) 109 and ref. therein; S. Godfrey and R. Kokoski, Phys. Rev. **D43** (1991) 1679; E.J. Eichten, C.T. Hill and C. Quigg, Phys. Rev. Lett. **71** (1993) 4116.
4. S. Godfrey and N. Isgur, Phys. Rev. **D32** (1985) 189.
5. D. Ebert, R.N. Faustov and V.O. Galkin, Phys. Rev. **D57** (1998) 5663.
6. CLEO collab., Phys. Rev. **D58** (1998) 052003 and ref. therein.
7. DELPHI collab., P. Abreu *et al.*, Nucl. Instr. & Meth. **A378** (1996) 57.
8. DELPHI collab., DELPHI Note 98-120 CONF 181 and ICHEP'98-122 (1998).
9. DELPHI collab., DELPHI Note 98-128 CONF 189 and ICHEP'98-240 (1998).
10. CLEO collab., P. Avery *et al.*, Phys. Lett. **B331** (1994) 236; OPAL collab., K. Ackerstaff *et al.*, Zeit. Phys. **C76** (1997) 425; ALEPH collab., D. Pallin *et al.*, ALEPH 98-047 and ICHEP'98-021 (1998).
11. F. Becattini, Zeit. Phys. **C76** (1997) 269; J. Phys. **G23** (1997) 1933.
12. DELPHI collab., P. Abreu *et al.*, Phys. Lett. **B426** (1998) 231.
13. D. Melikhov, O. Péne, Phys. Lett. **B446** (1999) 336; P. Page, hep-ph/9809575.
14. Yi-Jin Pei, Zeit. Phys. **C72** (1996) 39.